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Simulation study of hybrid ground-source heat pump system with solar collectors

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A simulation model of a hybrid thermal heating and cooling system consisting of solar collectors, vertical borehole heat exchangers and heat pump is presented in this article. The system model is built in the “TRNSYS studio” simulation environment and allows to explore different modes of operation and to analyze an influence of system parameters on performance characteristics. The model describes the behavior of a real laboratory installation and will be used for the optimization of its operation and costs. TRNBuild application was used to design the building model and allowed sample way to change model properties. The developed model could be a useful tool in hybrid heating and cooling system design process. Simple procedure needed to adopt model to any different system size and components parameters.

Keywords: hybrid thermal systems, solar collectors, borehole heat exchangers, heat pump, TRNSYS model

INTRODUCTION

By applying in geothermal heat pump installation solar thermal collectors a long term sustainable system is achieving. The operation of the Ground Source Heat Pump (GSHP) system with solar thermal collectors includes multiple physical processes. They are: building load dynamics, heat transfer in the soil, heat pump dynamics, and solar thermal processes. For each process a different timescale is required ranging from a decade to minutes. Energy efficient heating and cooling of the building is a system that includes in itself heat pumps coupled to vertical, closed-loop borehole heat exchangers (BHEs). This system is not economically advantageous. If the main operational mode is heating, then heat pump takes heat from the ground, which reduces the temperature near the borehole. By reducing the temperature of the soil the coefficient of performance (COP) of the heat pump is reduced, too. This requires the injection of solar energy into the borehole array to raise the soil temperature. The costs are reduced by incorporating a solar collector system to the BHE [1]. The hybrid GSHP systems with solar thermal collectors have the following advantages:

- they can potentially expand the residential Ground Source Heat Pump market by allowing reduced BHE footprint in both heating and cooling dominated climates;
- solar thermal collectors can be used to balance the ground loads over the annual cycle, thus making the BHE fully sustainable;
- in cooling dominated buildings, use of unglazed solar collectors as a heat rejecter allows for passive heat rejection, in contrast to a cooling tower that consumes a significant amount of energy to operate with stringent maintenance needs;
- in heating dominated buildings, the hybrid energy source (i.e., solar) is renewable, in contrast to a typical fossil fuel boiler or electric resistance heater as the hybrid component.

Fig.1 shows an example structure of a family house with a hybrid geothermal heat pump system and solar collectors [2].

The design of the hybrid thermal systems depends on time-variated functions driven by weather conditions, ground loop temperature history, and solar radiation availability [3]. Such systems are too complex and their design requires prior modeling in order to obtain optimum configuration and performance. For this purpose the simulation system has been developed by using commercial software TRNSYS. It is flexible software designed to simulate the properties of transition processes in hybrid systems [4].

In this article a simulation model of a hybrid thermal heating and cooling system consisting of solar collectors, vertical BHE and heat pump is developed. The model may be easy modified and adopted to any system components size, parameter values and specific climate conditions.

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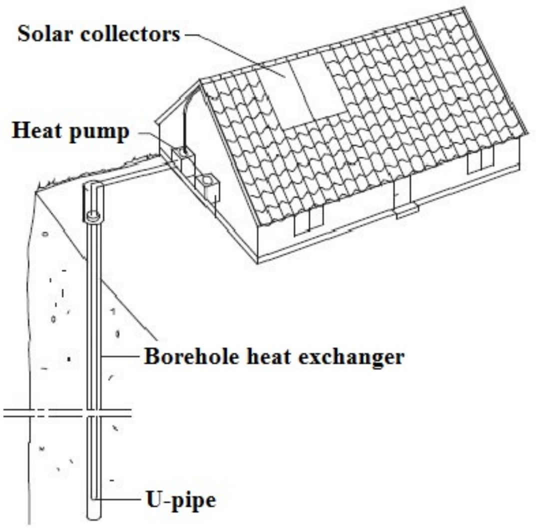

Fig.1. Example of a family house with hybrid Ground Source Heat Pump system and solar collectors [2]

SYSTEM COMPONENTS

A hybrid GSHP system with solar thermal collectors was constructed in the Technical University of Sofia, Plovdiv Branch. The principal scheme of the hybrid system is presented in Fig.2. The main system components are listed below.

Solar collectors:

- manufactured by PK Select-CL "Sun system" Ltd Bulgaria; flat glazed type;
- 3 pieces, each with 2,15m^2 cooper absorption surface;
- transparent coating of prismatic tempered glass with a thickness of 4,2 mm;
- 8 pieces heat-absorbing pipes;
- coefficient of absorption – 95%;
- coefficient of reflection – 5%;
- heat carrier – 10/90% water/propylene-glycol solution;
- the volume of heat transfer medium in the collector is 1,6 l with maximum flow rate of 50 l/m^{2}h;
- mineral wool with a thickness of d = 40mm is used for the insulation.

Borehole heat exchangers (BHEs):

- two borehole heat exchangers;
- the distance between the boreholes is 13m;
- borehole diameter is 165 mm;
- the boreholes depth is 50m;
- piping of high density polythene (HDPE) PE100 type with outside diameter of 32mm were inserted in the boreholes;
- single (first borehole) and double (second borehole) U-pipe construction;
- backfilled with grout material; piping of HDPE PE100 type with outside diameter of 32 mm were inserted in the boreholes;

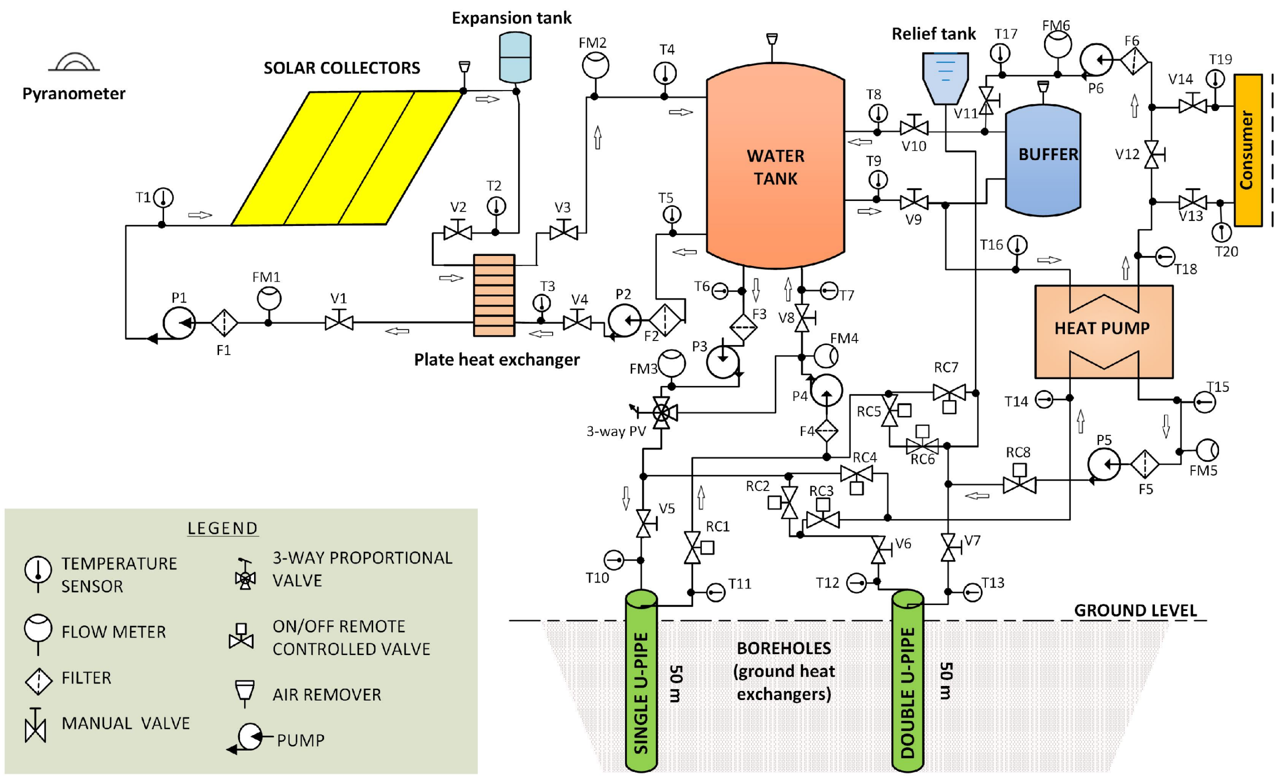

Fig.2. Schematic diagram of the hybrid Ground Source Heat Pump installation [5]

- single (first borehole) and double (second borehole) U-pipe construction;
- backfilled with grout material;
- the structure of the ground layers consists mainly of sands with different site of grains, clay and some gravel;
- the borehole thermal resistance and the ground thermal conductivity have been evaluated by a thermal response test (TRT); a device for it was developed at the TU-Sofia, Plovdiv Branch [6].

Heat pump:

- "Maxa" (Italy) heat pump model HWW-A/WP15 is used;
- heat pump type: water-water;
- maximum absorbed power– 1,2 kW (electrical);
- nominal cooling capacity – 4,6 kW;
- nominal heating capacity – 5,9 kW;
- compressor type – one rotary Scroll;
- oil charge – 0,4 kg;
- weight – 77 kg;
- power supply – 230 V, 50 Hz, single phase;
- refrigerant – 0,5 kg of R410A;
- input/ output connection diameter - 1 inch.

Heating conditions of the heat pump:

- temp. in/ out on condenser +40/45 °C;
- temp. in/ out on evaporator +15/10 °C.

Cooling conditions of the heat pump:

- temp. in/ out on condenser + 15/ 35 °C;
- temp. in/ out on evaporator +12/7 °C.

SYSTEM SIMULATION

For the system simulation commercial software TRNSYS [7] was used. In examining the various systems the following parameters are to be determined [2]:

- the net heat extraction from the ground;
- the use of electricity;
- the lowest and mean temperatures to the evaporator;
- the savings of electricity;
- the seasonal performance factor (SPF) of the system and coefficient of performance (COP) of the heat pump.

The structural components used in the system are listed below.

House Model

In creating building model component weather data reader and radiation processor Type 109, have been selected. Weather data for Plovdiv, BG (BG-Plovdiv-156250.tm2) are used. Type 109 is reading weather data from a data file at a regular time intervals, and converting it to a desired system of units. Then the processing of solar radiation data to obtain the tilted surface radiation and angle of surfaces incidence is performed for an arbitrary number of surfaces. This component is using a typical meteorological year format TMY2 [8].

The model of the house was designed in TRNBuild. Main house properties are listed in Table 1. To create files using the component type 56 generated with TRNBuild, the parameters are determined for the input variables. To create the model still additional components are necessary. They serve to process the data from the house:

Type 33 (Psychometrics) – calculates the corresponding wet bulb temperature and percent relative humidity and obtains the dry bulb temperature and relative humidity from weather data;

Type 69 – calculates the effective sky temperature for long-wave radiation exchange;

Type 667b – in this module, the fresh air temperature and relative humidity is fed by weather data component;

Type 24 – the Quantity Integrator was used to calculate the accumulated energy demand of different zones as well as the total accumulated energy demand of the house.

Table 1. Main house properties

Zone	Main properties
Basement	area of 67 m^2; volume of 201 m^3
1-st floor	area of 155 m^2; volume of 464 m^3
2-nd floor	area of 117 m^2; volume of 350 m^3
Attic	area of 120 m^2; volume of 240 m^3

Heat Pump Model

The water source heat pump model uses component of type 505. A single-stage liquid source heat pump, which works in two modes heating and cooling, is modeled through it. The heat pump model is designed for residential GSHP application [9]. This model is based on user delivered data files having catalogue data for the capacity and power, based on heat pump, the air flow rate, and the speed of flow rate setting up [10].

Borehole Heat Exchanger Model

To make the model of BHE thermally connected to the ground the component type 557 have been used. This component describes both: the vertical U-tube and vertical tube-in-tube heat exchangers. The soil temperature around BHE is calculated from the three parts: a local solution, a global temperature, and a steady-flux solution. The steady-flux solution is derived analytically, to solve local and global problems using finite-difference method. The superposition method is used to calculate the resulting temperature. This component was created by Department of Mathematical Physics at the University of Lund, Sweden [10, 11]. In this model four layers of ground are described. To calculate storage volume equation (1) is used [12].

Storage Volume = π × *Number of Boreholes* × *Borehole Depth* × (0,525 × *Borehole Spacing*)^2 (1)

Storage Volume = 14633 m^3

A backfilled borehole with grout material (mixture of cement and bentonite with factor 0,5) was used to enhance the thermal transfer between the tubes and ground.

Solar Collector Model

Type 1 is used for modeling the thermal characteristics of system which consists of three connected flat-plate solar collectors. The incidence angle modifier is calculated by quadratic function Eqn. (2). From ASHRAE or an equivalent test the coefficients of the function (2) are presented [12]. Standard test for efficiency of the collector is compiled by a ratio of fluid temperature minus the ambient temperature to solar radiation. The temperature of the fluid is obtained by averaging the temperature of the inlet and outlet temperatures. The Hottel-Whillier equation [13] is used as a general equation of solar collector efficiency.

$$Modifier = a_0 - a_1 \frac{\Delta T}{L_T} - a_2 \frac{(\Delta T)^2}{L_T}, \quad (2)$$

where:

ΔT is the difference between the inlet and ambient temperatures, °C;

L_T radiation is trapped on the solar collector, kJ/h.m^2;

a_0, a_1, a_2 are thermal efficiency coefficients [14].

Water Tank Model

Component Type 4 is selected for this model. It is intended to stratified storage tank with variable inlets and uniform losses. A water tank which comprises N (N = 6) fully-mixed equal volume segments is selected. The degree of stratification determined N. The storage tank can operate in one of three modes. The heat source for the water tank is water from the heat pump.

Ventilation Model

For the modeling of ventilation in the house component Type 667b is used. It is of air-to-air heat recovery type. As an input parameters a relative humidity, ambient temperature, flow rate and the second floor temperature are used in this model. Relative humidity and temperature of the HRV are outputs of the module.

Fig.3 shows the complete model of the hybrid system composed in TRNSYS studio.

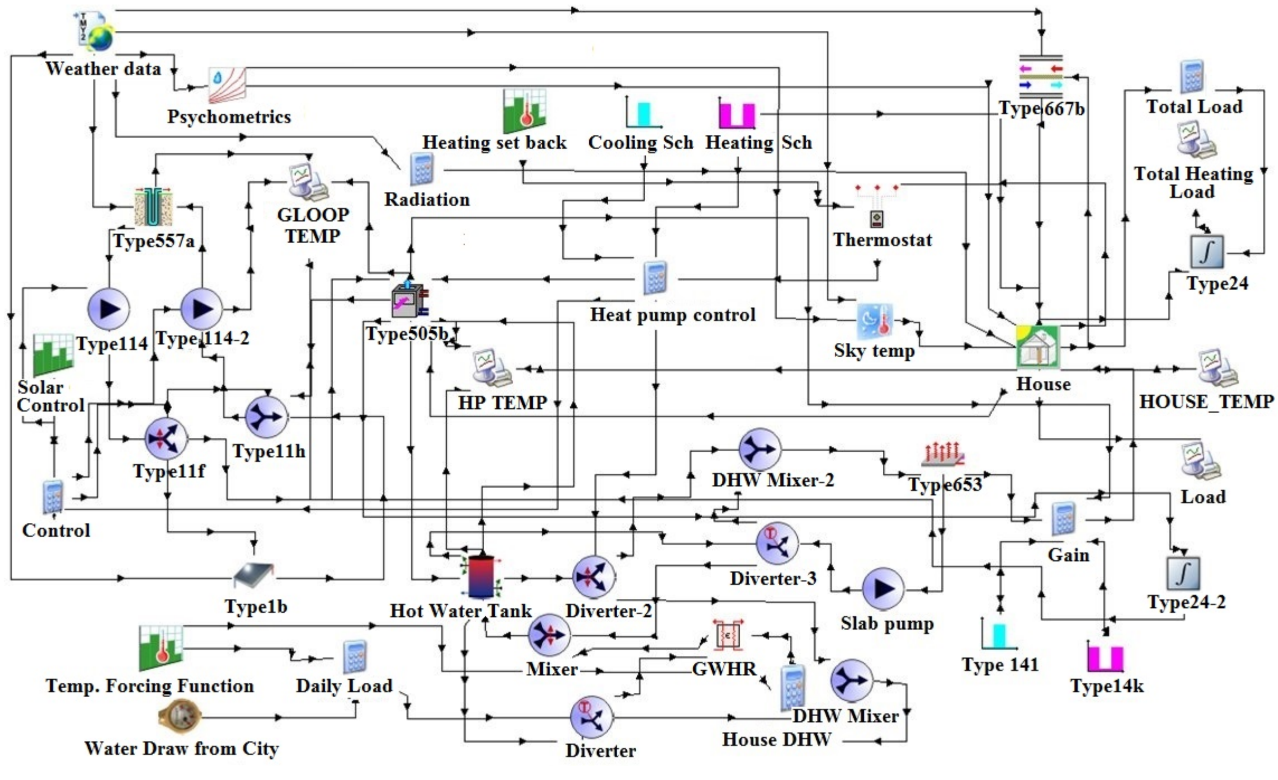

Fig.3. The structure of the model in TRNSYS Simulation Studio

SIMULATION RESULTS

In this study, the energy simulations run in the case with fixed solar collectors and GSHP. The house model describes four zones: basement (zone volume of 201 m^3), 1-st floor (zone volume of 464 m^3), 2-nd floor (zone volume of 350 m^3) and attic (zone volume of 240 m^3). The simulated heating load values for different zones as well as the total energy heating demand are presented on Fig.4. It may be mentioned that the main part of the heating power is spent for two zones: 1-st floor and 2-nd floor. The attic is not heated. The basement is heated, but at a lower temperature settings in a temperature controller.

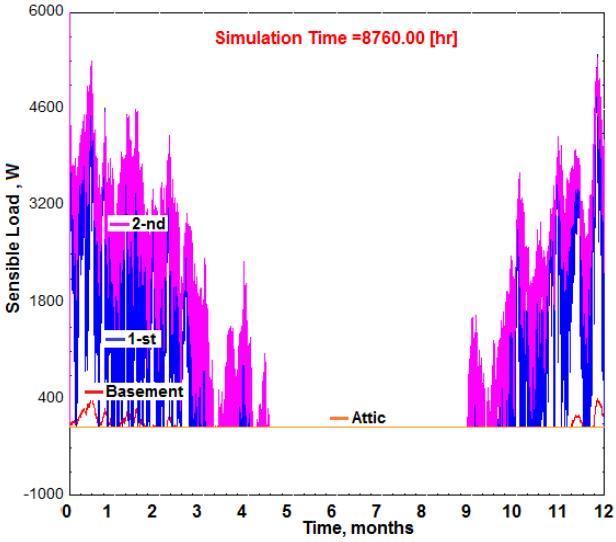

Fig.4. Simulated heating load for one typical year

Total heating energy demand of the house has been calculated by the integration of power in different zones and then by summing. Estimated annual values are shown in Fig.5. Yearly a quantity of 19,5 MJ required for the house heating.

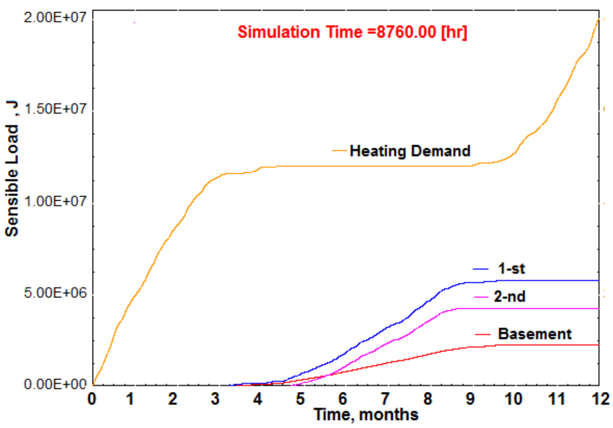

Fig.5. Simulated annual total heating and cooling demands

The annual cooling demand of the first, second floors and the basement has been calculated. The reported values are 5,8 MJ, 3,6 MJ and 2,2 MJ accordingly. The yearly simulation results for temperature values at different zones are shown in Fig.6. High quality of regulation may be observed. The temperature values in regulated areas vary in 1 degree region.

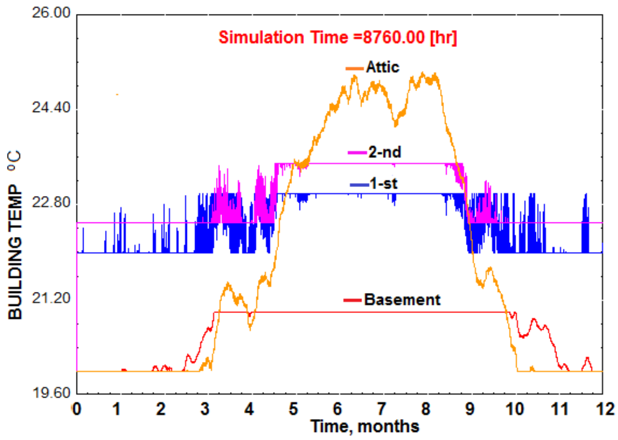

Fig.6. Yearly simulation of temperature values at different zones

CONCLUSIONS

A hybrid geothermal heat pump system with solar thermal collectors was constructed in the Technical University of Sofia, Plovdiv Branch. Simulation model of such systems have been developed in TRNSYS Simulation Studio. Running simulations showed that ground source heat pump systems with solar collectors are very perspective solution in a high efficiency building heating and cooling installations. The following conclusions have been made:

1. The developed model could be a useful tool in hybrid heating and cooling system design process. Simple procedure needed to adopt model to any different system size and components parameters. The designer has only to change: the building plane and requirements; the type, size and parameters of the solar collectors, boreholes; heat pump; and the weather data;

2. A thermal response test (TRT) has to be previously performed for the purpose of validation of the borehole model parameters;

3. Additional experimental works in each design case are needed to validate model parameters;

4. System energy simulations carried out by the model allow the designer to optimise system components size and to reduce the costs;

5. The developed model may be used to optimize modes of system operation and to build and approve new control algorithms that lead to higher energy efficiency.

ACKNOWLEDGEMENTS

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